"Grimsvötn: Pressure of Crystallization and Magma Chamber Depth"

Senior Thesis

Submitted in partial fulfillment of the requirements for the

Bachelor of Science Degree

At The Ohio State University

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The Ohio State University

2012

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Acknowledgements

I would like to thank Dr. Michael Barton for all of his help and resources throughout this research project. Without his patience and willingness to always help no matter how busy I was, this thesis would have never been completed. So for that I am forever thankful. I would also like to thank my research partner Andrew Tenison who was always there to help me whenever I needed it and always took time out of his own research to make sure I was keeping up with my own. Thanks to the whole School of Earth Sciences because without you I would have still been stuck in that dreadful engineering department. I would also like to thank my family, friends, and Aubrey for all of their support and help along the way; I truly could not have done it without you all. Lastly I would like to thank Bob Simons at Cohort Software who gave me his software program for free in order to make the graphs and diagrams with ease.

Abstract

Volcanoes in Iceland pose an enormous threat to not only the environment but a large portion of the population due to the sheer number and potential destruction that lies under each one. Grimsvötn, being the most frequently erupting volcano in Iceland, is a great locality to develop more of an understanding into how these volcanoes actually work and what we can do to better prepare ourselves for future events. Basaltic glass samples were taken and analyzed using various methods in order to determine partial pressures of crystallization. From this we can deduce magma chamber depth and interpret through various petrological methods, a possible system which lies beneath the volcanoes. As a result of completing this procedure we have concluded that the data are best explained by the presence of a complex plumbing system, consisting of both a shallow and deep chamber, and plexus of small chambers at various depths, or a deep chamber linked to the surface by dikes. Similar models have been proposed for the plumbing systems beneath other volcanoes in Iceland.

Introduction

Iceland is an excellent place to study volcanoes because of the unique geological location astride the Mid-Ocean Ridge, for the sheer number of active volcanoes and the high frequency of eruptions and for the known impact of past eruptions on the global environment. One of the obvious targets for detailed study is the volcano with the highest frequency of eruptions in Iceland, Grimsvötn. Being the most seismically active and frequently erupting volcano on the island, there are still many unanswered questions about this volcano, which is located beneath the large Vatnajökull icecap (http://www.volcano.si.edu/world/volcano.cfm?vnum=1703-01=, May 25). There has been relatively little recent research done on this particular volcano, and most of the research available has focused on the Laki eruption of 1783(Thordarson et al. 2007). Little is known of the volcanic plumbing system, although this is clearly important for understanding eruptive activity and for predicting future eruptions. The results of geodetic and seismic studies have been interpreted to indicate the presence of a rather shallow magma chamber, but this is not consistent with the preliminary results of petrological studies aimed at quantitatively estimating the pressure of partial crystallization of Grimsvötn magmas (Kelley and Barton, 2008). The availability of the new data potentially

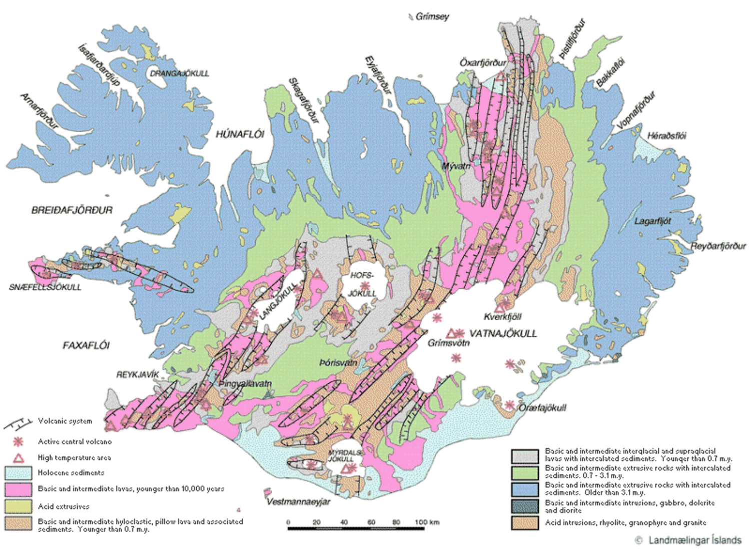

Figure 1: Aerial map of Iceland showing also the locations of Grimsvötn and the Vonajökull ice sheet under which lies the volcano. (http://notendur.hi.is/oi/iceland_excursion.htm, May 25)

allows tighter constraints to be placed on the plumbing system under this volcano and comparison with results obtained for other Icelandic volcanoes. Major oxide data for glasses can be used to calculate pressures and temperatures, as well as to plot variation diagrams that allow potential relationships between sample compositions and the depth of partial crystallization (Kelley and Barton, 2008) Such relationships might provide evidence for evolutionary processes such as magma mixing or assimilation, thereby providing insight into the dynamics of magma ascent and intra-crustal storage in volcanoes above the mantle plumes.

Grimsvötn lies mostly under the vast Vatnajökull icecap along the eastern rift zone, where the caldera lake is covered by a 200 meter thick ice shelf. The geothermal activity under the ice shelf is the cause for frequent and deadly jökulhlaups or glacier outburst floods. With it being one of the most active volcanoes in the world, all the information to help when it erupts is of tremendous use.

Objectives

The overall goal of this proposed research is to determine the pressure of partial crystallization, and to infer the magma chamber depth under the Grimsvötn volcano using chemical analyses of glasses compiled. The rationale for this study is that studies based on geodetic and seismic data have been used to infer a rather shallow chamber at a depth of approximately 5.4 km, yet petrologic data suggest partial crystallization at higher pressures and are possibly consistent with the presence of a complex system of chambers throughout the lower and upper crust (Kelley and Barton, 2008) It is very possible that a smaller, shallower chamber is fed by much deeper and complex systems of magma chambers and dikes. The goal of this research is to utilize more recent chemical data for glass samples from Grimsvötn to test this hypothesis.

Geological Background

Iceland lies on both sides of the Mid-Ocean Ridge and was created by seafloor spreading that began about 55 Ma. The crust is unusually thick ranging from about 20 km to upwards of 40 km, which indicates higher degrees of melting in the underlying mantle than occurs beneath normal ridge segments (Kelley and Barton, 2008). This possibly reflects the presence of a mantle plume or upwelling which is presently centered below the northwest edge of the Vatnajökull ice sheet. Most seismic and volcanic activity takes place in a roughly 50 km wide rift zone, which marks the sub-aerial exposure of the Mid-Atlantic Ridge and in three flank zones. Estimates of the depths of the various magma chambers beneath Iceland's volcanoes range from 1.5 to 35 km in the crust (Kelley and Barton, 2008).

Grimsvötn is the name of the volcano and associated dikes in Southeast Iceland. They central volcano is located beneath the south-central part of the vast Vatnajökull ice sheet in the highlands of Iceland. The summit caldera is covered by a 200 meter thick ice sheet, and geothermal activity causes frequent and deadly jökulhlaups or glacier outburst floods. Grimsvötn lies in the eastern rift zone and has the highest eruption frequency of all Iceland volcanoes, including an immense climate changing event known as the Laki fissure eruption, which occurred from 1783 until 1785 (see following section). Many of the eruptions occur under the ice sheet. This poses many problems other than just those associated with lava flows, because when the magma erupts it comes into contact with ice it produces highly explosive eruptions and large amounts of melt water resulting in jökulhlaups. When jökulhlaups occur from Grimsvotn, they flow almost fifty kilometers to Skeidarasandur, an outwash plain, and drain into the North Atlantic.

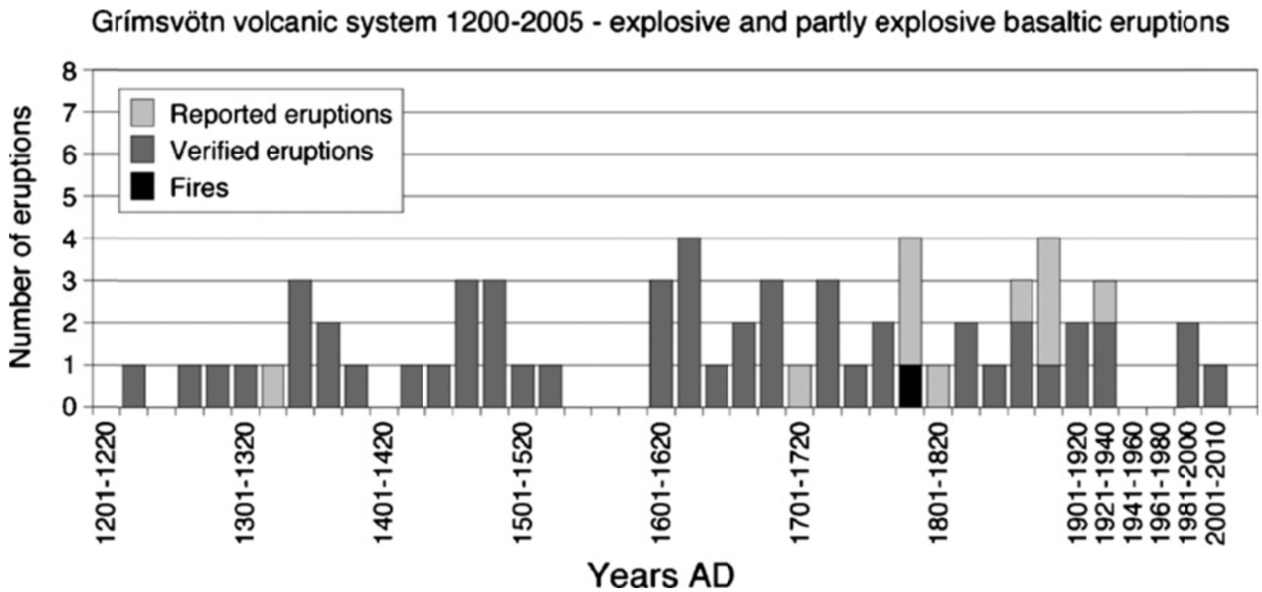

Figure 2: Frequency of eruptions on the Grimsvotn volcanic system since 1200a.d. Two gaps in activity, 1540–1600a.d. and 1940–1980a.d. are evident from the data, as well as five frequency peaks that are spaced at intervals of 100–160 years. Pre-1300a.d. data are incomplete and therefore not included (Thordarson, 2007).

Grimsvötn and Laki

Grimsvötn is responsible for one of the largest basalt eruptions in recorded history. In 1783, a fissure that is part of the Grimsvötn volcanic system, known as Laki, opened up and vented an estimated 14 cubic km of basaltic lava and pyroclastics for nearly 9 months. This eruption also triggered great floods of melt water resulting from the magma interacting with the overlying glacier and also released large quantities of poisonous hydrofluoric and hydrochloric acid and sulphur dioxide into the air. The eruptions lead to the demise of over fifty percent of their population. (Thordarson et al. 2003). It is estimated that this eruption killed over 20,000 people in Britain alone and at least half of the Icelandic population due to the temperature drop resulting from the volcanic aerosols that blocked out the sun and caused crop failures and droughts across the globe (http://news.bbc.co.uk/2/hi/8624791.stm , May 25).

Methods

Several petrologic methods are available to quantitatively estimate the pressure of partial crystallization. The most appropriate method for use with a large number of samples is based on comparing the compositions of erupted melts with those of liquids lying along P-dependent phase boundaries. Many basalt magmas crystallize olivine (ol), plagioclase (plag) and clinopyroxene (cpx), and their compositions can be compared with those of liquids lying along the *ol-plag-cpx* cotectic boundary. The effect of pressure on the latter has been determined experimentally, (eg. O'Hara, 1968; Grove, 1993), and can be seen by recasting melt compositions into normative mineral components and projecting phase relations onto pseudoternary planes in the system CaO-MgO-Al_2O_3-SiO_2. Projection of phase relationships from *plag* onto the plane *ol-cpx-qtz* using the recalculation procedure of Walker et al. (1979) clearly shows the shift of the *ol-plag-cpx* cotectic towards *ol* with increasing P (Fig. 3). Crystallization pressure can be qualitatively estimated by comparing the projected compositions of natural samples with the locations of cotectics on such diagrams, and this method has been used to estimate crystallization pressures for Hengill by Trønnes (1990), for Bláfjall Table Mountain by Schiellerup (1995), for Kistufell by Breddam (2000), and for Theistareykir by Maclennan et al. (2001).

The shift of the *ol-plag-cpx* cotectic towards *ol* and *plag* (see O'Hara, 1968; Grove, 1993) reflects the different pressure dependencies of *cpx-liq*, *ol-liq* and *plag-liq* equilibria, and results in decreasing CaO and increasing MgO and Al_2O_3 contents of melts with increasing P. Weaver and Langmuir (1990), Langmuir et al. (1992), Danyushevsky et al. (1996), Yang et al. (1996), and Herzberg (2004) have proposed models to quantitatively estimate the crystallization pressure based on such relationships. These models are all calibrated with experimental data, and that selected for use is that of Yang et al. (1996), who present equations which describe the composition of liquids along the *ol-plag-cpx* cotectic as a function of P and T. Hence, the composition of the liquid is used to predict the P (and T) of saturation with *ol, plag* and *cpx*, and these predicted liquid compositions are converted to normative mineral components and projected from *plag* onto the plane *ol-cpx-qtz* using the procedure of Tormey et al. (1987) (see Grove et al. 1993) assuming that ΣFe=FeO. Comparison of observed glass compositions and predicted liquid compositions indicates the pressure of partial crystallization.

"Unlike the graphical methods others have used, pressure have been calculated using the algorithm of Kelley and Barton (2008).An assessment of the accuracy (~0.13 GPa, 1σ) and precision (~0.08 GPa, 1σ) of calculated pressures is given by Kelley and Barton, (2008). Analyzed volcanic glasses provide reliable records of the liquid compositions of erupted magmas. Glass analyses were compiled from various papers; Guilbaud et al. (2007), Thordarson (2007), and Meyer et al. (1985). This compilation comprises 105 samples collected in and around the Grimsvötn volcanic system. The reported compositions of these samples were used to calculate pressures of partial crystallization by comparison with the compositions of liquids lying along the olivine-plagioclase-clinopyroxene cotectic (Yang et al, 1996).

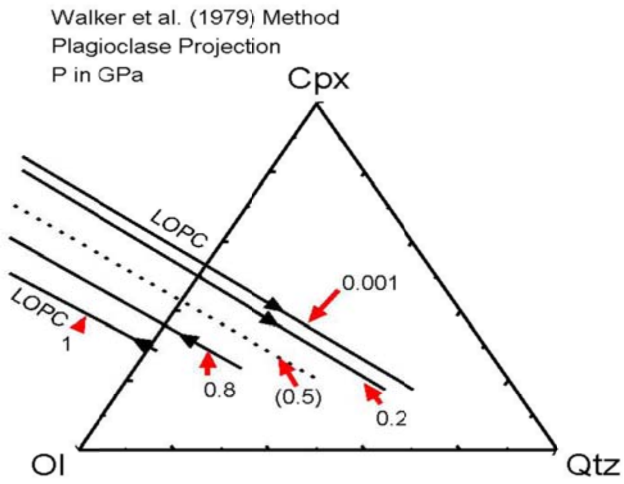

Figure 3: The *ol-plag-cpx* cotectic at different pressures, showing the evolution of a melt as described by Walker et al., (1979)

Results and Discussion

Only basaltic volcanic glasses were considered in this research because the models to calculate pressure are calibrated only for basalt liquid compositions. Variation diagrams plotted using these analyses are broadly consistent with magma evolution via fractional crystallization with removal of olivine, plagioclase, and clinopyroxene as solid phases (Figure 6). Pressures were calculated using the excel spreadsheet which was described by Kelley and Barton in their 2008 paper. All of the results are used in this work: none of the calculated pressures is negative, a problem encountered with pressures calculated for some MORB data sets (Barton, personal communication, 2012), and all of the calculated pressures yield errors smaller than the maximum uncertainty (.13 GPa) expected for this method.

The results of all of the calculations can be summarized as follows; the average pressure of crystallization of all samples is 3.7 Kbar ± .9 with the majority lying between 2 and 5 Kbar. The maximum pressure was 7.6 Kbar whereas the minimum was .98 Kbar. The corresponding average magma chamber depth is 13.0 km ± 3.3. The maximum chamber depth is26.9 km and the minimum is of 3.4 km. The average temperature of crystallization was 1169.94˚C with a range from1192.55 ˚C to1149.19 ˚C.

These results agree quite well with those obtained by Kelley and Barton (2008) using a smaller data set. These authors calculated an average pressure of crystallization of 3.1 Kbar with a range from 5.1 to .98 Kbar. The differences in the average and maximum pressures are due to the larger data set used in the present study. The relatively wide range of pressures calculated for Grimsvötn lavas possibly indicates the presence of both shallow and deep chambers, a plexus of small chambers between a maximum and minimum depth, or a magma body in the lower crust linked to the surface by a system of conduits and dikes (Kelley and Barton, 2008) The lack of correlation between calculated pressure and MgO (Figure 6) argues against the presence of extensive sill-like bodies at any depth in the crust, and suggest that partial crystallization may have occurred in dike-like conduits as the magmas ascended to the surface. The minimum pressure determined in this study (0.98 Kbar) suggests that the final pause in ascent of some magmas occurred at a depth of 3.4 km. This depth is within the range of depths suggested for a shallow chamber on the basis of geodetic and seismic observations, and indicates some consistency between the results obtained using petrological methods and those obtained using other methods.

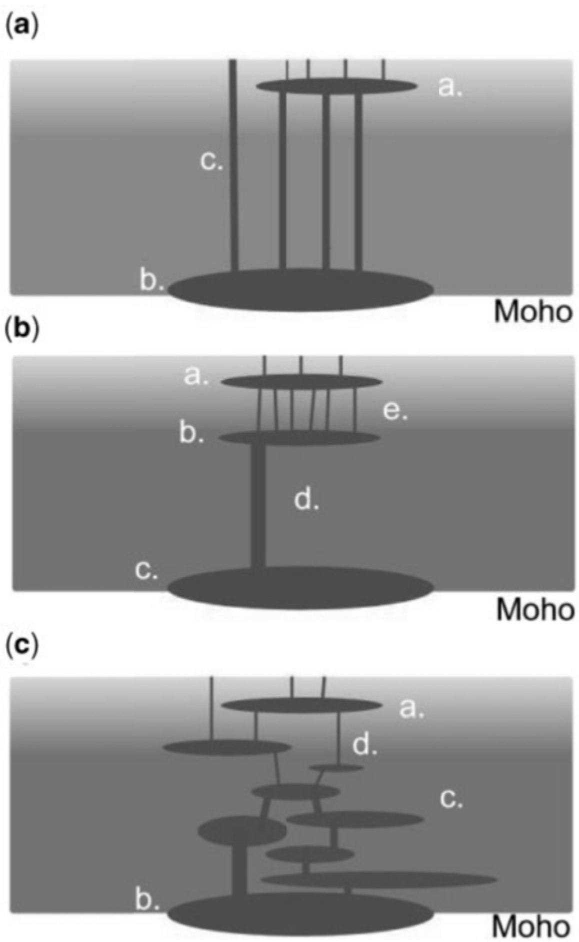

Figure 4: This figure explains what Kelley & Barton predicted would be under various volcanoes throughout Iceland, specifically (c) which is the prediction for both shallow (a) and deep (b) along with a piping system of interconnected conduits and dikes (d) and (c). (Figure from Kelley and Barton, 2008)

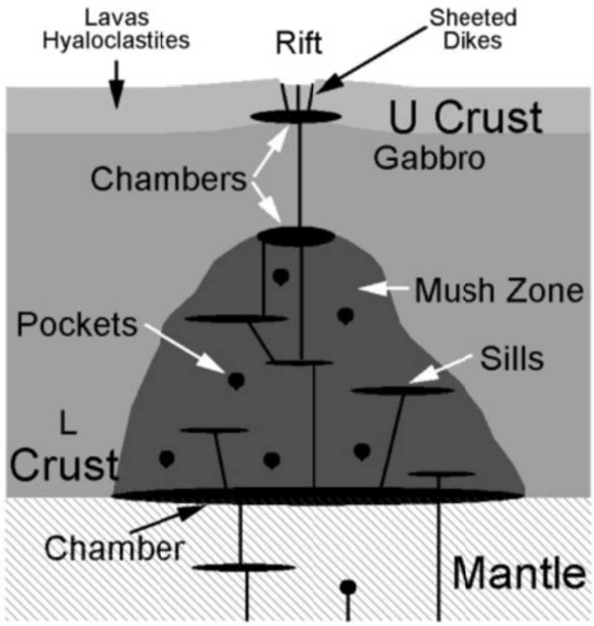

Figure 5: This is a model for the crust below the Grimsvötn volcano, with many pockets of magma and dikes feeding magma from the mantle up through to the surface. The presence of a single shallow chamber is not supported by the results, and it is more likely that a system of chambers and dikes exists over a relatively wide range of depths, and that crustal accretion to occur in a mush-like zone (Kelley and Barton, 2008).

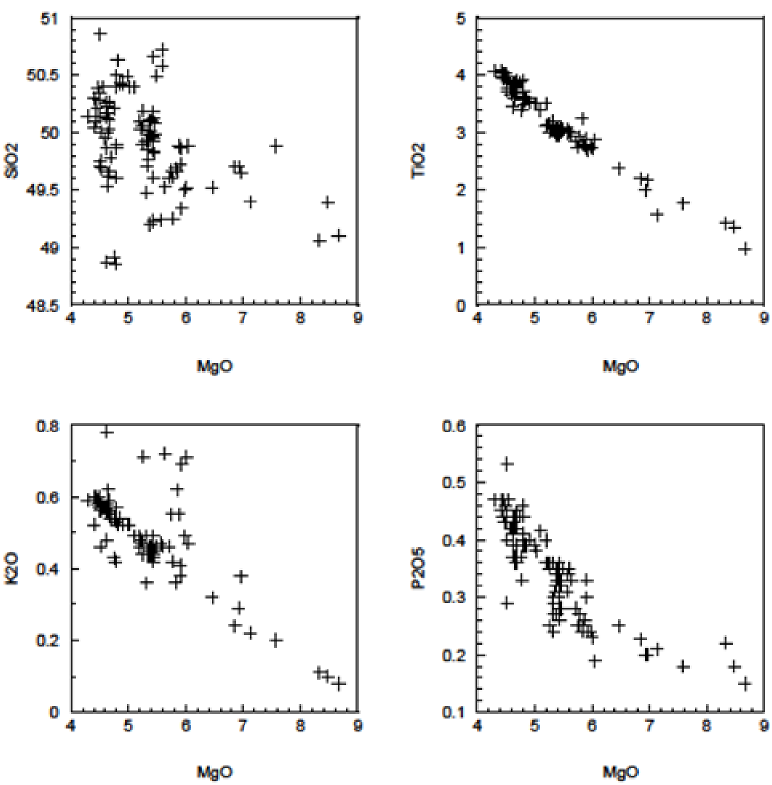

Figure 7: MgO vs Al_2O_3, CaO, and CaO/ Al_2O_3 (wt %) illustrating chemical variations produced by differentiation. The decreasing Al_2O_3 (Wt%) with decreasing MgO (Wt%) implies crystallizations of *ol* with *plag*. While decreasing CaO (Wt%) with decreasing MgO (Wt%) shows crystallization of *cpx*.

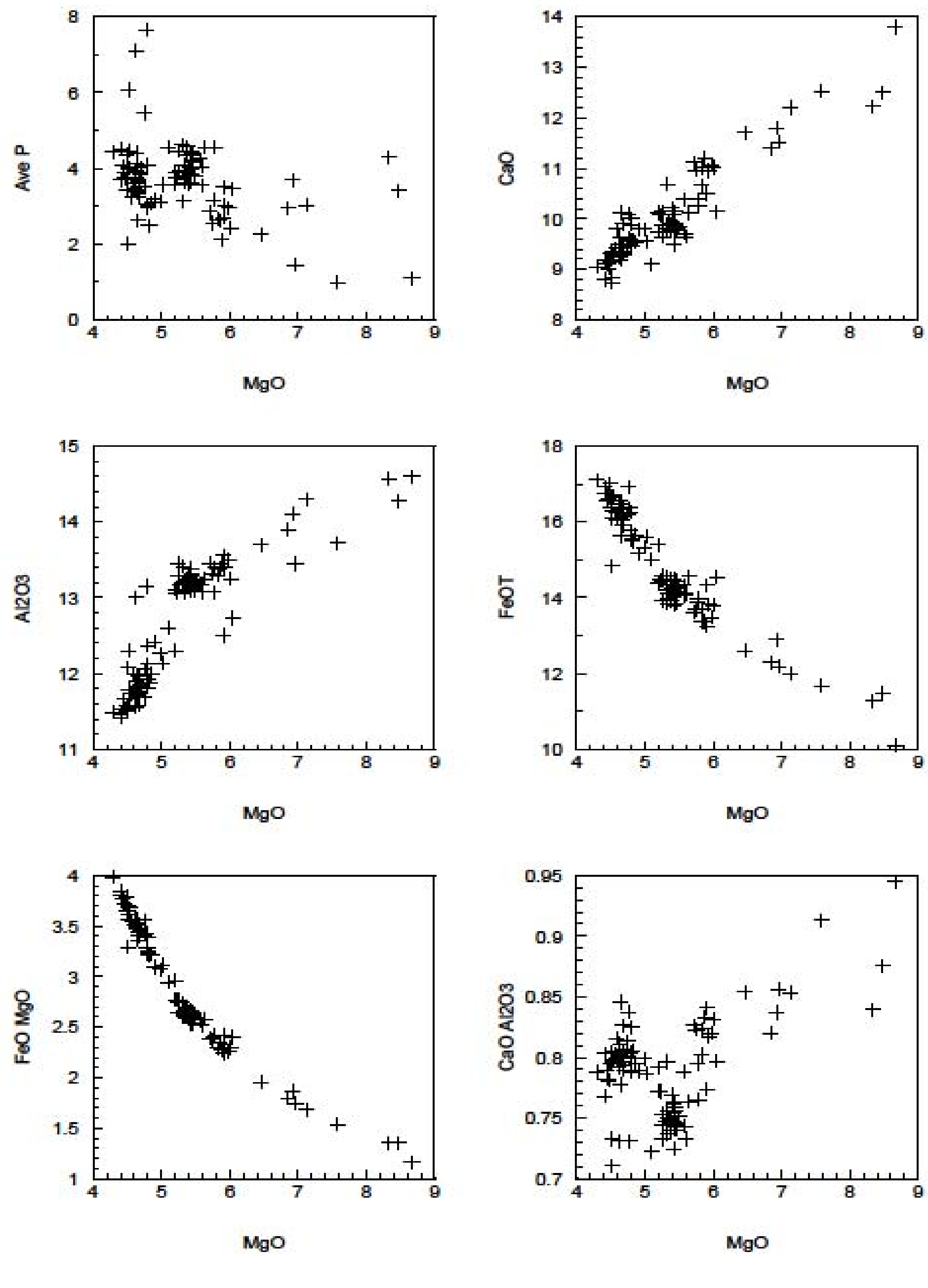

Figure 7 cont'd: Variations of Al_2O_3, CaO, and CaO/ Al_2O_3 with MgO allow identification of the mineral phases that crystallized during magma evolution. The decrease in Al_2O_3 with decreasing MgO is consistent with crystallization of *olv-plag-spinel*, and many Icelandic basalts contain phenocrysts or microphenocrysts of these minerals (e.g. Meyer et al., 1985). However, the strong decrease in CaO and slight decrease in CaO/Al2O3 with decreasing MgO requires crystallization of cpx (Herzberg, 2004).

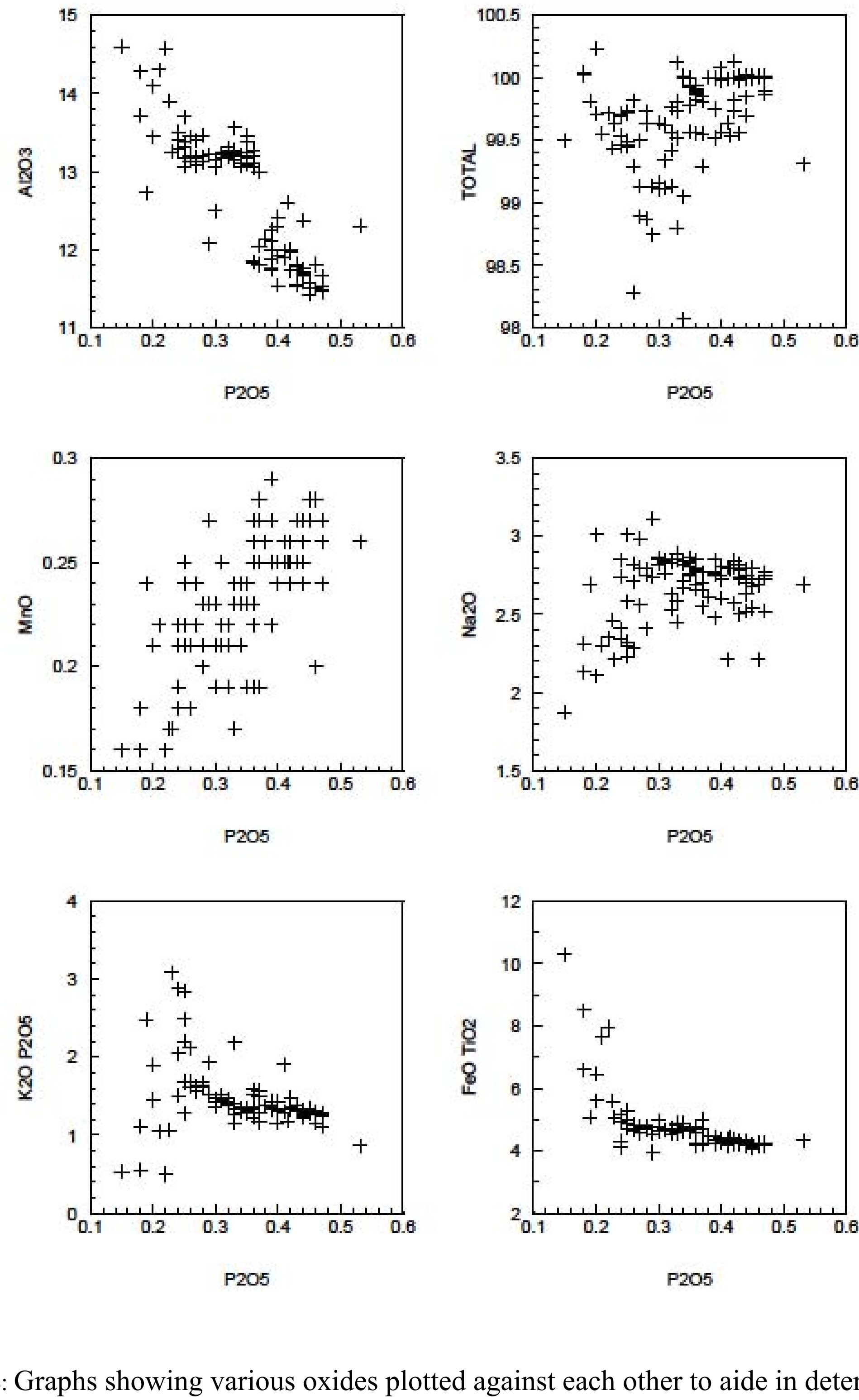

Figure 8: Graphs showing various oxides plotted against each other to aide in determining what is crystallizing and at what pressure.

Conclusions

The original purpose of this research was to determine the magma chamber depth under the Grimsvötn volcano using a well-established petrologic technique. The results indicate that the Grimsv□tn magmas partially crystallized over a relatively wide range of pressures, and are therefore inconsistent with the presence of a single (sill-like) magma reservoir at any depth in the crust. The data are best explained by the presence of a complex plumbing system, consisting of both a shallow and deep chamber, and plexus of small chambers at various depths, or a deep chamber linked to the surface by dikes. Similar models have been proposed for the plumbing systems beneath other volcanoes in Iceland.

Future Work

Additional petrologic studies could shed further light on the nature of the plumbing system beneath Grimsv□tn. Collection and analysis of new samples of lava and hyaloclastite will allow pressures of partial crystallization to be calculated for a much larger data set, potentially providing statistical evidence for a preferred pressure of crystallization and therefore a likely depth of a major magma reservoir. In addition, detailed studies of mineral compositions in individual samples will potentially allow the polybaric crystallization history of the Grimsv□tn magmas to be deciphered, providing both qualitative and quantitative information about the intracrustal plumbing systems and ascent histories. Such data, combined with the results of studies of mineral zoning patterns to evaluate the importance of processes such as magma mixing and magma-crust interaction, will shed light on magma dynamics beneath this volcano. Determination of magmatic water contents is another important aspect of the pre-eruptive history of Grimsv□tn magmas that I did not consider. Water contents can be estimated by petrologic methods using major-oxide glass compositions, but are best determined directly on melt inclusions in minerals using specialized techniques such as ion-microprobe analysis. Pre-eruptive water contents affect calculated pressures of partial crystallization, though the exact magnitude of this effect has rarely been determined in previous studies. Water dissolved in magma also affects physical properties such as density and viscosity, and hence influences magma ascent rates.

The additional studies outlined above will provide better estimates of the depth of major magma storage, of eruption triggers (eg. magma mixing and recharge of the plumbing system), and of magma flow rates. The results of these studies will therefore allow determination of the time lapse between the onset of seismic unrest and eruption. Such knowledge is essential for predicting eruptions, and for minimizing loss of life during eruptive episodes.

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